Postural Sensitivity to Visual Flow in Aging Adults With and Without Balance Problems

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Background. This study tested balance behavior of young adults and aging adults with and without balance problems in response to visual flow from a moving visual surround.

Methods. Balance behavior was indexed by force plate measures of maximum anterior/posterior displacement of the center of foot pressure and horizontal shear forces. The sample included normal young adults (n = 13; mean age 23 years, ± 7.5), normal aging adults (n = 13; mean age 76 years, ± 6.5), and aging adults with balance problems not directly attributable to a diagnosable neurological disease or dysfunction (n = 13; mean age 79 years, ± 5.8).

Results. The balance-affected aging group had statistically greater sway responses than the young group when the stimulus was unexpected (as in the first trial; p < .05). Some individuals in each group had large responses that were statistical outliers from the group median. The balance-affected group had significantly greater shear forces than the young group.

Conclusions. Greater sway responses suggest over-reliance on visual cues for posture control in the balance-affected aging group, which may be related to underlying, borderline somatosensory deficits, as indicated by the patterns of subclinical indications for somatosensory impairments on neurological exams in this group. Visually sensitive postural control, however, may issue from several different underlying processes. Elevated shear forces during balance responses in the balance-affected group suggest a greater use of hip movements in addition to ankle movements for postural adjustments.

An overall decline in postural stability occurs with increasing age in elderly adults (1–4), and is associated with an increased incidence of falls. What remains less clear are the specific changes in postural control that result in loss of stability. There is, nonetheless, a growing appreciation that changes over time in sensory and motor processes (5–7) contribute to global balance problems in some aging persons.

For example, elderly adults may be more sensitive to visual cues for balance control than are young adults (1,8,9). Sensory information provided by the visual, vestibular, and somatosensory systems is used to mediate balance control. These inputs are not entirely redundant, as the different sensory systems appear specialized for sway detection and stabilization within different domains of sway frequencies and amplitudes (10–12). As adults age, they tend to lose receptors and neurons contributing to the function of the vestibular system (13,14). They also show reduced somatosensation, particularly from distal muscles and joints important for balance control (4,15,16).

Teasdale and associates showed that a small degradation in somatosensory information was very detrimental to postural stability in aging subjects as compared to young adults when vision also was withdrawn (17). Even young subjects, when deprived of full proprioceptive information from the limbs, appear more sensitive to visual inputs for control of balance (18). In a recent study, Wade and colleagues tested elderly and young subjects in a “moving room” (19,20) in order to determine their sensitivity to the perception of self-motion specified by an optical flow field that falsely signaled self-sway (21). The elderly group moved more than the young group in response to global movements of the visual surround. The responses, however, suggested generalized destabilization rather than specific “tracking” of sway to the movement direction of visual flow.

It is possible that these results reflect a general shift toward increased reliance on vision for balance control in some elderly persons. Such a shift could result in a greater risk of falling if an older adult also had: (a) the diminished visual perceptual skills that often accompany aging (22,23); and/or (b) impaired sensory organization capabilities. Sensory organization processing has been defined as the reweighting of sensory inputs used in postural control in response to changes or decrements in the quality of any balance-relevant sensory information (24).

In addition to changes in sensory processes, changes in motor processes may be associated with stability problems in aging adults. For example, there may be shifts in the postural strategies used for balance control. When balance is threatened, young adults tend to compensate with ankle sway if the threat is not great. It is hypothesized that if standing balance is threatened sufficiently, the young adult will use movements initiated at the hip (“hip strategy”) to quickly reposition the center of mass above the base of support. Horak and Nashner (25) showed that young adults tend to use a “hip strategy” when they are unable to generate torque at the ankle joint — for example, when standing on a beam.

In contrast, when the balance of many older adults is threatened — even to a small degree — they tend to use a “hip strategy” more frequently than young adults (26). Horak and associates hypothesized that this is due to a loss of peripheral somatosensation or weakness in ankle joint muscles, creating a condition in which hip muscles are used...
preferentially (6). Increases in hip sway movements during upright stance also can be induced experimentally in young subjects by ischemic blockade of inputs from ankle muscle proprioceptors (27).

Since hip movements for upright balance control increase the horizontal shearing forces between ground and plantar sole (26), the risk of slipping is increased. Hence, increased instability and the resulting falls in elderly people may be associated with the mechanical consequences of making balance-recovery movements about the hip.

Aging persons, however, do not form a homogenous group, and not all elderly people suffer losses of balance or falls (28–30). Consequently, increased sensitivity to visual cues for balance control and/or the tendency to use hip movements for balance recovery may be characteristics of posture control that are not found in healthy aging individuals who have no problems with balance. In their study on the effects of a visual stimulus on the postural sway of three different categories of aging adult "fallers," Ring and colleagues showed some support for the notion that balance function and sensitivity to visual cues are related (31). These researchers found that elderly people who had fallen very recently swayed more in response to a computer-generated optical flow stimulus than did subjects with falls sometime during the past year or those with no falls during the past year.

In the present study, we investigated: (a) sensitivity to visual flow cues for balance control, and (b) the tendency to use a hip strategy to recover balance under these conditions. We asked: do these characteristics of postural control vary with age or balance function? We hypothesized that older individuals with balance problems, as compared to older people without balance problems and healthy young adults, would show: (a) greater response in the form of increased sway to an unexpected visual flow stimulus (19,20), and (b) an inability to attenuate the sway response across repeated trials when the stimulus no longer was unexpected. We also hypothesized that balance responses in the balance-affected aging group would be associated with higher horizontal shear forces, suggesting the use of a hip strategy for recovery of balance.

METHODS

Subjects. — Aging volunteers were assigned to one of two groups, based upon falls or balance problems experienced in daily life activities and also upon scores from a postural Sensory Organization Test (SOT) previously administered to each subject (32). The healthy Aging group members (n = 13; 68–91 years old; 5 male, 8 female; mean = 76 years ± 6.5) had no self-reported falls or losses of balance and no more than one loss of balance on the SOT. The Symptomatic aging (n = 13; 68–89 years old; 2 male, 11 female; mean = 79 years ± 5.8) self-reported falls or losses of balance in life activities and had more than one loss of balance on the SOT. All of the aging subjects in this study tested in the normal range on manual clinical exams of ankle and knee flexor and extensor muscle strength and visual field screening. There was no significant age difference between the two aging groups, t(24) = 1.44, p > .05. A Young control group consisted of normal healthy adults (n = 13; 16–43 years old; 2 male, 11 female; mean = 23 years ± 7.5) who had no known health or balance problems.

Apparatus. — A force platform (AMTI model OR6-5-1000) measured forces and moments relative to a set of XYZ axes. Signals were sampled at 500 Hz using a Watscope A/D processor (Northern Digital, Ontario, Canada). A moving visual surround (MVS), 6' wide × 8' long × 8' wide, enclosed on three sides and above, was suspended from the ceiling by 4 chains, one at each corner, and surrounded the force platform 2 inches above floor level. The surround could be moved translationally in an anterior/posterior plane aligned with the y axis of the platform, which was the direction of A/P sway of our subjects. The open end of the moving visual surround (MVS) had a crossbar along the bottom edge. A trained experimenter, kneeling at a point directly behind the subject and gripping this crossbar, manually pushed or pulled the MVS approximately one second after data collection had begun. The same experimenter manipulated the visual surround for all subjects and for all of the pilots to this study. Consistency in movement duration was achieved by the experimenter silently counting elapsed time on an analog watch as the surround was moved. An accelerometer (Entran EGC-240) recorded room movements. The inside side walls were covered with alternating 2-inch-wide black and cream vertical stripes. The front wall was covered with black felt with a 1-inch diameter cream-colored dot (visual fixation point) at subject's eye level. From this fixation point the bilateral side striping boundary subtended 45° retinal eccentricity at subject's eye level. Two 60 watt bulbs illuminated the interior of the room. Movement of the MVS created flow in a subject's visual periphery that could be misinterpreted as sway in a direction opposite room movement, whereupon compensatory sway in the direction of room movement occurred. Subjects were protected from falling by a tethered safety harness.

Dependent measures (CoP and Fy). — Visually evoked balance responses were indexed by the peak-to-peak range of anterior/posterior (A/P) center of foot pressure (CoP) displacements (mm) following onset of MVS movements for each discrete trial and for the duration of each oscillation trial. The CoP is the location of the vertical ground reaction vector from a force platform, and it is a representation of the body’s neuromuscular response to movements of the center of gravity (33). CoP indirectly reflects sway behavior when the subject stands quietly. It was felt that A/P displacements of the CoP would reflect directionally specific postural adjustments related to A/P movements of the MVS. If the visual flow created by MVS movements is misinterpreted as self-sway, the would-be correct compensatory movements are in the A/P direction. CoP maximum displacement values submitted to statistical analysis were normalized to foot length and expressed as a percentage of the total anatomical length of the foot. These values then represented relative rather than absolute displacements of the CoP.
The force platform Fy channel measured the magnitude of the voltage range (V) of horizontal shear forces acting along the platform y axis (anterior/posterior direction). Horizontal shear forces (Fy) were normalized to subject weight and expressed in volts.

**Procedures.** — Subjects stood barefoot on the force platform in their normal stance position. Baseline measures of CoP and Fy were made for 15 seconds with the subject in Quiet Stance with eyes open (QSO) and with eyes closed (QSC). Additional voluntary sway trials were collected but not considered for this analysis. Three conditions of 7-second MVS trials followed: (a) Away trials (total of 5) in which the MVS was pushed forward 35 cm at an average velocity of 10 cm/s, moving the front wall away from the subject and stopping at the maximum position; (b) Return trials (total of 5) during which the MVS returned from the maximum forward (away) position to neutral position (these "catch" trials were not analyzed); and (c) Oscillation trials (total of 2) wherein the MVS moved back and forth a distance of 15 cm at a rate of approximately .3 Hz for 14 seconds. Oscillation trials were given after the MVS return from Away trial 2 and after the MVS return from Away trial 4. Inter-trial interval was varied from 20–45 seconds, except after a trial in which the subject became greatly destabilized. In this case, the inter-trial interval was 2–5 minutes. The experimental data set included 9 trials in the following order: quiet stance eyes open, quiet stance eyes closed, first Away, second Away, first Oscillation, third Away, fourth Away, second Oscillation, fifth Away.

**Data analysis.** — Descriptive analysis was done on the raw CoP time series traces. The measures from QSO and QSC trials first were tested for any statistically reliable differences between groups in the baseline measures of CoP and Fy. CoP measures for the "novel" first Away trial were submitted to a one-way analysis of variance (ANOVA). A 3 × 9 (Group × Trial) repeated measures multivariate analysis of variance (MANOVA) then was conducted to determine if the pattern of responses varied by group across the repeated trials. Fy measures were submitted to a separate 3 × 9 (Group × Trial) repeated measures MANOVA. Post hoc analyses were conducted when significant differences were found (p < .05).

**RESULTS**

**Center of Pressure (CoP)**

The groups did not differ on baseline measures of CoP either with eyes open [F(2,36) = 1.85, p > .05] or eyes closed [F(2,36) = 2.43, p > .05]. Likewise, no significant differences were found for baseline Fy [F(2,36) = .10, p > .05] and [F(2,36) = 3.07, p > .05], respectively. Thus, it was assumed that group differences in the MVS trials could not be attributed to a shift in baseline quiet stance measures.

Displacements of the CoP in response to the MVS ranged from a few millimeters to more than 20 centimeters. Normalized maximum CoP values ranged from 3% of foot length to 100% of foot length, which was a loss of balance (subject 8, Figure 1A). Displacements of 10% or more were associated with clearly observable postural sway following room movements. Positive skewing and extreme outliers characterized each group’s distributions (Figure 1 A, B, C). In oscillation trials (Figure 2), CoP time-series traces were periodic, reflecting the relative phase-locking (34) between postural sway and the .3 Hz driving frequency of visual motion. However, the amplitude of displacements of the CoP varied greatly (compare Figure 2 s8 and y38). Also, higher frequencies were quite marked in the raw traces from some subjects (Figure 2, s8, s12, a17).

**Novel first trial.** — The raw CoP time-series traces for the "novel" trial across all subjects showed a range of deflection sizes from very small to very large in the direction of room movement, at latencies of approximately 600–800 msec after movement onset. Averaged raw CoP time-series traces for each group for the "novel" trial are shown in Figure 3. These figures were constructed using all subjects from each group; therefore they do not represent a specific response, but illustrate the average response in the first trial for the group. All traces show an initial adjustment to posture in the direction of room movement with a secondary, corrective response in the opposite direction. The Symptomatic group trace, however, shows larger initial displacement, as well as continuing instability following the initial response that persists after the surround has stopped moving between elapsed seconds 4 and 5 (Figure 3).

To determine any statistically reliable differences between the groups in the "novel" trial, the normalized CoP displacement scores were submitted to a one-way ANOVA, which yielded a significant group main effect [F(2,36) = 3.61, p < .05]. Post hoc analysis found the Symptomatic group significantly higher than the Young group in CoP displacements in response to the unexpected MVS movement [F(2,36) = 3.61, p < .05]. The Aging group did not differ from either the Symptomatic or Young groups. Great variability of scores was observed in the Symptomatic group (Figure 1). Eight of the Symptomatic individuals responded to the "novel" trial with magnitudes of CoP displacements above the mean of the Young group. Seven Symptomatic subjects were more than three SDs above this mean. On the other hand, four subjects were below the Young mean.

**Repeated trials.** — A 3 × 9 (Group × Trial) repeated measures MANOVA was employed to determine if the groups differed on their pattern of responses across the different trials. This analysis did not distinguish the groups [F(2,36) = 1.95, p = .158]. There was a significant trial main effect [F(8,288) = 8.50, p < .001], but no significant Group × Trial interaction, indicating the pattern of responses was similar across groups. Post hoc tests [F(8,342) = 4.95, p > .001] revealed the pattern to be: (a) displacements of the CoP significantly greater than Quiet Stance for the "novel" first trial; (b) attenuation of response to nonsignificance on the second trial; (c) increase to significance for the first Oscillation trial (when the visual stimulus was first altered, from discrete to oscillatory); and (d) attenuation thereafter. In sum, our Young and Aging groups were found to have similar patterns of responses across the repeated trials.
Figure 1. Maximum displacements of the CoP expressed as a percentage of foot size for each subject for each trial. Points marked with asterisks are outliers from the group median for that trial (> 3 box lengths above the upper quartile of a box plot).
As can be seen in Figure 1, however, the individual pattern of responses differed greatly across individual subjects (asterisks mark subjects whose scores were extreme outliers from the group median for that trial [i.e., > 3 box lengths from the upper quartile of a box plot]). Certain individuals from each group, many of whom had scores that were outliers in their group's distribution for particular trials, appear to be most sensitive to the visual cues in the 'novel' trial and/or to the change in stimulus experienced on the first Oscillation trial. For instance, all subjects displaced the CoP in a sinusoidal pattern, coincident with room oscillations, even though in some cases the subject's movements were very small and the subject reported no feeling of actually having moved. Only subjects s8, s12, a25, a17, y33, y31, and y29 displaced the CoP to magnitudes that corresponded with large postural adjustments or destabilization (Figure 1). Thus, subjects with great sensitivity to optical information for balance control, and those with low sensitivity, can be found in all three groups.

**Horizontal Shear Forces (Fy)**

To determine if horizontal shear forces varied with age or balance-function grouping, the Fy measures were submitted to a 3 x 9 (Group x Trial) MANOVA with repeated measures. There was a significant group main effect $[F(2,36) = 3.32, p < .05]$. Follow-up analysis revealed the Symptomatic group generated significantly greater shear forces (Fy) than the Young group in the first and second Away trials (Figure 4). The normal Aging group did not differ from either of the other two groups. There also was a main effect of Trial $[F(8,288) = 8.26, p < .001]$. Post hoc tests indicated that responses to the first Away and the first Oscillation trials were associated with significantly greater shear forces than the control condition of QSO.

**DISCUSSION**

There is previous evidence of increased sensitivity to visual inputs for balance control (21), and an increased probability of a "hip" postural strategy for adjustments to balance in aging people (26). A premise of this study was that aging individuals with balance problems would show greater visual sensitivity and greater use of a hip postural strategy when responding to a visual stimulus than both...
normal young and normal, healthy aging individuals who have no problems with balance.

Visually sensitive posture control. — Significantly greater visual sensitivity in "novel" or unpredictable settings was found only in our balance-affected aging group as compared to the young group. Interestingly, this aging group did not show statistically significant increases in sway when vision was absent (QSC), suggesting it is the unexpected incongruence of vision with other balance-relevant inputs that is destabilizing. All of our aging individuals correctly misperceived the visual flow as their own A/P sway, and they perceived the visual flow as their own A/P sway, and they destabilizing. All of our aging individuals correctly misperceived the visual flow as their own A/P sway, and they initially responded with compensatory movements in the direction of room motion. The balance-impaired subjects, however, tended to have longer periods of destabilization which persisted for several seconds after the initial response to an "away" movement of the visual surround (Figure 3).

In formulating a dynamic theory of action-perception patterns in the context of the "moving room," Schöner (34) suggested that an estimate of the stability of a postural state is the time course of relaxation back to the original postural state (relaxation time) following a perturbation. Our averaged CoP time series traces (Figure 3) suggest a prolonged relaxation time to the pre-perturbed postural state (quiet stance) in the balance-affected aging group members following transient, unexpected visual flow stimuli. By this assessment, quiet stance, as a postural state, is less stable in these individuals. From the perspective of dynamic theory, effective damping (34) of fluctuations in postural behavior decreases relaxation time and increases the stability of a postural state. Declines in effective damping may contribute to instability in some aging persons. Examples of what may be poorly damped higher frequency postural behavior fluctuations can be seen riding the .3 Hz driving frequency of the CoP periodic movement in the time-series traces of several of our aging subjects (Figure 2).

The nature of the relationship between balance impairment and visual sensitivity is not clear. For instance, does a tendency toward visual sensitivity increase with the onset of stability problems (reactive vigilance), or, does a tendency to rely upon vision or some gradual shift toward reliance on vision for balance control actually contribute, over time, to instability (proactive vigilance, with a poor result)?

While the data here cannot answer this question, results from clinical neurological exams (32) previously administered by a neurologist to 11 of the 13 aging adults from the Symptomatic group in this study provide some insights. All but one of the balance-impaired aging adults tested had indications of somatosensory impairment in the lower extremities. The individuals with the largest (Figure 1A, subject s4) and smallest (Figure 1A, subject s9) responses to the "novel" trial had, respectively, the greatest (4) and least (0) number of clinical signs for somatosensory impairment. Future research on balance function in aging certainly should include complete clinical and functional neurological exams for all participants.

Based on results from the present study and observations from the neurological exams, we hypothesize that sensitivity to optical flow information for balance control increases not necessarily with age, but with a decline in balance-related somatosensory function. It is possible that a decline in vestibular function may contribute to increased visual dependence as well, although none of our aging subjects reported a history of vestibular problems. It also is possible that some aging subjects might have slight central integrative problems; however, the rapid attenuation of responses for most subjects suggests quick integration and reorganization of postural control. For subjects s8 and s12, on the other hand, slower attenuation of responses suggests problems at a central integrative level in addition to any subclinical peripheral impairments.

If there is a decrease in threshold sensitivity level for visual motion cues (21) in our symptomatic group, we suggest it results, operationally, in a compensatory shift toward increased reliance on vision for balance control. Under normal circumstances, vision has a stabilizing influence on posture (19,35). Increased reliance on vision, however, can be destabilizing when a large portion of the visual world moves relative to the inertial frame of an observer, as occurred in our MVS paradigm. Thus, balance-affected aging persons who are overly sensitive to visual cues for balance control could experience episodes of disequilibrium when something unexpected happens in motion-rich visual environments (e.g., riding an escalator, walking in a shopping mall, or driving on busy streets).

Individual differences. — Our results not only indicate greater likelihood of overreliance on visual inputs in the balance-affected group, but also show that postural sensitivity to visual flow can occur in apparently healthy aging and young individuals as well. This suggests that the phenomenon arises from not one, but perhaps a variety of underlying processes. (Psychologists have classified those unable to ignore misleading visual cues as "field dependent" (36), but no studies as yet have shown a specific relationship between
that phenomenon and the aspects of postural control considered here.)

Individuals in this study could be categorized, generally, into groupings based upon response patterns: (a) minimal response on all trials (e.g., subjects s9, a20, y32); (b) small responses in the "novel" trial which increased in later trials (e.g., subjects a17 and y31); (c) moderate to large responses in the "novel" trial with rapid attenuation thereafter (e.g., subjects s4, s3, s6, a19, a15, a24); and (d) large responses in the "novel" trial, some attenuation of response in the second trial, with an increase in response to the first oscillation trial (a new visual context) (e.g., subjects s8, s12, a25, y29, and y33). These observations are indicative of the heterogeneity in postural control found within groups and also within individuals, which increases the difficulty of diagnosing, treating, and ameliorating postural dyscontrol. Moreover, sensitivity to visual flow for postural control appears to be a "shared" characteristic among certain individuals from each of our groupings, which argues against the usefulness of a visual flow test (31) for sensitive screening of balance function. Further research is needed to identify the set of variables that influences postural response magnitudes in a visual flow paradigm.

Hip postural strategy.—This study also sought to determine if the magnitude of horizontal shear forces varied with age or balance-function grouping during responses to a visual flow stimulus. Hip movements are known to transmit shear forces to the support surface (6,25), whereas movement at the ankle joints generates torque (25). Increases in sway velocity might also be a contributing factor in generating shear forces (37). However, higher sway velocities for hip movements are expected as the time constant for hip-bending movements is significantly faster than for ankle movements (38). Our results show that the balance-affected aging group tended to have higher shear forces than the young control group. From this, we infer that subjects in the balance-affected aging group tended to use more hip movements than did the young adults when adjusting posture in response to visual surround movements.

Horak and associates hypothesized that pathology (as in, for instance, a decrease in somatosensory inputs) causes a shift toward the increased use of a hip strategy in older adults (6). Our results contribute further evidence in support of the notion that an increase in the probability of selecting a hip strategy for balance recovery movements is associated with some abnormality that affects the postural control system ("less successful" aging), rather than constituting a normal part of the aging process.

ACKNOWLEDGMENTS

This study was supported by grant AG-05317 from the National Institute on Aging to Dr. Marjorie Woollacott.

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Received April 20, 1995
Accepted September 15, 1995